STUDIES FOR STUDENTS

RELATIONS BETWEEN CLIMATE AND TERRESTRIAL DEPOSITS[1]

JOSEPH BARRELL
Yale University, New Haven, Conn.

GENERAL INTRODUCTION

The environment of the lands may be classified into three fundamental and independent factors—the relations to the surrounding seas, the topography which forms their surfaces, and the climates

[1] Presented in abstract before the Geological Society of America, December 26, 1906. The term terrestrial deposits has special reference here to fluvial and pluvial deposits rather than glacial, lacustrine, and eolion deposits.

[2] Parts II and III will be published in later numbers.

which envelope them; each of major importance in controlling the character of the lands and the evolution of their inhabitants.

The relations of the lands and seas of previous ages is the one of these environmental conditions which has been longest under investigation, since the seas have left a positive record of their invasions in the form of marine sedimentary strata and the remains of the inhabiting organisms.

The topographic changes of the lands of earlier ages give problems of equal importance, both in connection with the history of crustal movements, as sources of the sedimentary rocks, and in the evolution of terrestrial life; now raising mountain barriers and again opening fields for migration and expansive evolution. But until recent years the problem of restoring earlier land-forms had not attained to a systematic and scientific state. That knowledge of the topographic history of the land should be slower in development than the relations of land and sea is seen to be natural when it is considered that each erosion surface is made only through the destruction of the preceding land-form, with the result that the earlier leaves in the volume of land history, contrary to that of the sea, are destroyed in the making of the last, and it is only through processes of deduction that the earlier stages may in a general way be restored.

The third great problem of terrestrial environment, the succession of ancient climates, lags still farther behind in development, but is no less important in a complete understanding of the history of the earth and its inhabitants. This lack of development is doubtless due to the intangible nature of climate and the absence of direct record of its geologic changes. When it is considered, however, how fundamental are the relations of continental deposits to the climates in which they are formed, it is seen that the record of geologic climates, while indirect and largely awaiting interpretation, is nevertheless in existence.

The significance of salt and gypsum deposits on the one hand or of glacial deposits on the other is of course universally recognized, but these are the marks of climatic extremes. The causes of climatic variations, as distinct from the record, have likewise in recent years received a great amount of attention, with the result that a considerable body of knowledge has taken the place of previous speculation. But

what are the geologic records of that great variety of climates which, excluding the desert belts of the world, reach at present from the equator to the polar zones? They may be studied most favorably in ancient terrestrial deposits, since these are free from the contributory record of the sea, and, as it is the problem of the average climates which it is sought to investigate, it is especially in ancient fluvial and pluvial deposits rather than in deposits of desert or glacial origin that the record is to be found. In such river deposits each stratum represents an old land surface, the seat of abundant animal and vegetable life, sealed and protected instead of destroyed, by the making of the succeeding land record. In such deposits the evidence most usually studied is that from the teeth and feet of animal fossils, or the nature of vegetable remains. But many continental deposits are without fossils and many groups of organisms show a wide climatic range, so that it is very desirable that other features constantly present, such as the chemical, textural, and structural characteristics of the strata, should be available for the climatic interpretation. The significances of such features have of course not entirely escaped attention, the presence of red in shales or sandstones is sometimes cited as evidence of derivation from a deeply decayed and highly oxidized regolith; or the existence of a conglomerate whose pebbles are of vein quartz as evidence of the thorough decomposition of an ancient soil. But such statements have been made without a preliminary investigation into all the possible modes of origin, and it will be found that in the following pages other interpretations are pointed out. The problem, then, in the present paper is to separate the influence of the climatic and topographic factors in the making of fluviatile continental sediments. In seeking for data to draw the lines more closely it is found that the relations of climate to the nature of the land waste and river sediments have attracted the attention of relatively few explorers and scientists. Such exceptions must, however, be noted, as Blanford and Oldham, Walther, Hilgard, Merrill, Russell, Davis, and Huntington. These men, with a few others, have largely supplied the data which make the following articles possible.

The mode of treatment adopted is to divide the influence of climate upon fluvial and pluvial deposits into three parts: first, the influence on the kind and quantity of the material eroded, allowing for the

effects of various land reliefs and lithologic characters; second, the influence upon the sediments in the region of deposition, allowing for the various geographic conditions under which the deposit may take place; third, the relations of climate to transportation by running water. Each of these relations forms a largely independent problem and by the concurrence of evidence from them other factors may be eliminated and a fair degree of certainty attained in regard to the climatic conditions existing during the formation of ancient stream deposits.

The first part, dealing with the relations of climate to erosion, is necessarily largely physiographic and, in the case of sediments which are carried long distances, is of less final influence than the conditions under which the sediments are deposited and those of the preceding transportation. The purpose of the whole paper is, however, not physiographic but stratigraphic. For this reason it is the relation of physiography to erosion and the consequent supply of sediments which is dwelt upon, rather than the discussion of the land-forms as an end of investigation. Owing to this somewhat unusual use of physiography as well as the desire to make the discussion more complete for students in other branches of geology, it is necessary to go over some ground which is familiar to physiographers. Even from a physiographical standpoint, however, it is thought that a brief general discussion of all the climatic factors influencing erosion is not without its value, since it is found to suggest some new points of view upon several old problems.

For the elaboration of the second and third parts, those upon the relations of climate to terrestrial deposition and the preceding transportation, sufficient reason is found in the existence of diverse views held by many working geologists upon the significance of various stratigraphic characters; and, furthermore, in the general conclusion that climate is a factor comparable to disturbances of the crust or movements of the shore line in determining the nature and the variations in the stratified rocks of continental or off-shore origin, thus playing a part of large, though but little-appreciated, importance in the making of the stratigraphic record.

The investigation was instituted to see to what extent profound climatic variations, complicated doubtless with some tectonic movements, could account for the great contrasts in the Lower and

Upper Carboniferous formations of eastern Pennsylvania; formations which had been found by the writer from field investigations to be continental in origin and therefore their contrasted features not to be attributed to changes in the relations of land and sea. As an illustration of the importance of the climatic factor in sedimentation, it may be stated that an application of the conclusions of this paper goes to show on several lines of evidence, which it is hoped to publish in the near future, that the changes from the red beds of the Catskill formation, several thousand feet in thickness, to the gray Pocono sandstones with a maximum thickness of 1,200 to 1,300 feet, then to the sharply contrasted red shales and sandstones of the Mauch Chunck, 3,000 feet in maximum thickness, and back to the massive white conglomerates of the Pottsville conglomerate, 1,200 feet in maximum thickness, followed by the coal measures, are all the result of increasingly wide swings of the climatic pendulum which carried the world from Upper Devonian warmth and semi-aridity to Upper Carboniferous coolness, humidity, and glaciation.

PART I. RELATIONS OF SEDIMENTS TO REGIONS OF EROSION

Introduction

The larger rivers of the world, of which the Missouri and the Nile may be cited as striking examples, frequently rise in a climatic zone entirely distinct from that of the mouth. Such rivers usually flow for some hundreds of miles across low-lying country after escaping from the mountains, and carry nothing coarser than fine sand in their lower reaches, the dominant deposits over the surfaces of the large deltas being a great volume of clay and loam. That the climatic conditions under which the sediment is supplied at the source, has an appreciable influence even in these extreme cases is shown by Walther, who points out that the alluvium of the large tropical rivers is usually red in color while that of the Ganges and Mississippi, brought to the limits of the tropics from temperate regions, is gray instead of red.[1]

In shorter river systems, however, not only is the climate of the headwaters more closely related to that of the alluvial plains, but both the climatic and geographic conditions existing over the former region

[1] *Einleitung in die Geologie,* 1894, p. 815.

will notably modify the character of the sediments laid down upon the latter. It is necessary, therefore, to consider geographic factors as well as climatic, and to begin at the river's source. The geographic and topographic relations in the regions of erosion existing during a distant epoch cannot, however, be directly ascertained by observation of the existing rocks, as may the conditions in the region of deposition. These relations may, furthermore, in their effect upon the alluvium, simulate and mask the climatic effects to some extent. As a result it is impracticable to make fine distinctions in climatic cause over the regions of erosion, and in general only those types of climate which markedly affect the quantity and kind of land waste need be considered. These may be classified as of four types, as follows: warm and rainy, warm and arid, cold and rainy, cold and arid; truly glacial climates being excluded from the scope of the paper.

Character of Rocks Supplying Sediment

SIMILAR EFFECTS FROM LITHOLOGIC AND CLIMATIC CAUSES

In alluvial deposits the nature of the rocks supplying sediment is a matter of importance. A basic igneous rock, for instance, even in a subarid climate, such as exists over the Deccan of India and the northwestern United States, may give rise to a large amount of ferruginous clay containing mineral fragments other than quartz, and of various sizes. After sufficient transportation and sorting such clays would be the dominating deposits, and except for a greater content of lime, must closely simulate clays from well-decayed normally acidic rocks of a more pluvial climate. Again, a region of calcareous rocks will furnish a large amount of lime in solution, and this, by cementing the alluvium of the delta, as for example, in that of the Rhine, may cause the river deposits of a humid climate to resemble in this respect the alluvium of subarid regions. Further, the material derived from rocks of a sedimentary nature owes part of its character to a previous cycle of erosion and deposition under different climatic and geographic conditions.

ELIMINATION OF LITHOLOGIC FACTORS

This possibility of confusion between climatic and lithologic influences over the region of the headwaters may be obviated to a large extent, first, through the determination of the source of sediments and, if

this region is still above the sea, observation as to the kind of rocks now outcropping and probably present at that time; second, by a detailed study of the nature of the sedimentary particles (Sorby, Bonney, and others have shown to what an extent microscopic study of sedimentary materials may indicate the lithologic nature of the source);[1] third, by comparing the particles in deposits of dissimilar nature but of similar coarseness or fineness accumulated in successive epochs in the same region, and presumably from the same general source. For example, the material forming the coal-measure shales and sandstones of eastern Pennsylvania is of about the same grain and doubtless from the same ultimate source as the Upper Devonian and Subcarboniferous shales and sandstones of the same region. Scattered microscopic particles of feldspar in one of these formations and an absence of them in another may be taken as due to a difference in topographic or climatic conditions of origin in the region of the headwaters, and not due to derivation from unlike lithologic sources.

The preceding statements regarding the influence of the sedimentary source must not be allowed, however, to give an exaggerated importance to the lithologic character of the original rock; important near the regions of erosion, it diminishes with the distance of transportation. In regard to this matter E. W. Hilgard states:

> Alluvial soils are to a certain extent dependent upon the character of the rocks and surface deposits occurring within the drainage area of the depositing stream. As a rule their composition is much more generalized; and their character as to the relative proportions of sand and clay is essentially dependent upon the velocity of the water current.[2]

This diminution in influence of origin with distance of transportation is due partly to the contributions from tributary streams coming from somewhat different geologic provinces, partly to continued decomposition of the sediments during transportation, tending to leave similar insoluble residues, but largely to the sorting action of the water in separating unlike constituents. The sediments from dissimilar geologic provinces, therefore, are apt to consist of similarly classified products, such as ferruginous clays and siliceous sands,

[1] T. G. Bonney, Presidential Address, Section C—Geology, *Proceedings of the British Association for the Advancement of Science*, 1886, pp. 601–21.

[2] *Soils in the Humid and Arid Regions*, 1906, p. 13.

though the total amounts of these may hold to each other entirely different proportions. It is to be concluded that the nature of the parent rock is best reflected by the nature of the sediment where this is but slightly transported, but may show in minor degree for long distances.

Relations of Rainfall and Topography to Erosion

INTERRELATIONS OF TOPOGRAPHIC AND CLIMATIC CAUSES

The relation between the topographic character of the land and the resulting sediment has been discussed by Bailey Willis, who points out that in the youthful topographic stages rock-breaking as a method of erosion dominates over rock decay; in topographic old age the reverse is true. The former supplies a maximum of unleached mechanical sediments; the second, a maximum of rock matter in solution.[1]

Under arid climates, however, and to a lesser extent in cold climates, the material derived from the rocks is characterized by the same dominance of disintegration over decomposition, even in regions of topographic maturity or old age; sun and wind serving to erode and transport rock material without producing rock decay. When swept to a distance by rivers and laid down upon flood-plains, there may be strong chemical resemblances between the sediments originating under such dissimilar conditions and consequently a resulting confusion between distinct topographic and climatic causes.

Furthermore, topography and climate not only have independent and sometimes similar effects upon the sediments, but have mutual effects upon each other. On the one hand, topography in its major features modifies climate, on the other, climate materially affects the minor features of topography.

Different kinds of climate and topography may, therefore, lead to various results, and a change in either the climatic or topographic factor in the regions of erosion may be expressed by a change in sedimentation over a distant flood-plain. In analyzing and separating these interrelations and simulated effects three kinds of topography may be considered: first, young and mountainous topography, characterized by deep and precipitous valley walls, high elevations,

[1] Studies for Students, "Conditions of Sedimentary Deposition," *Journal of Geology*, Vol. I, 1893, pp. 476–80.

and a maximum of naked rock surface; second, mature mountainous topography, marked by broadly V-shaped valleys, long slopes covered with soil and talus, and lower rounded summits; third, old topography, with widely opened, flattened valleys holding meandering rivers and with the interstream spaces no longer mountainous, but reduced to rolling hills. The four kinds of climate to be considered have already been mentioned as combinations of pluvial and arid, warm and cold.

YOUNG TOPOGRAPHY AND VARIOUS CLIMATES

Young and mountainous topography, as is well known, produces an intensification of climatic effects and a heightening of the climatic contrasts of nearby regions, inducing an extreme precipitation, often largely as snow, upon the windward slopes and to a lesser extent upon the leeward slopes, and resulting in semiarid or truly arid tracts farther to leeward. Rapid erosion will prevail in both regions, but the results are of essentially different characters. Where the precipitation is regular and not violent, that is, not as snowfall or irregular cloud-bursts, the rivers and valley walls tend to become graded, vegetation holds the soil to the slopes, and interstream erosion over the soil-covered regions is diminished, and the material carried away by the rivers is finer[1] and more thoroughly leached of its soluble elements.[2] Over the steeper slopes and along the streams, however, erosion may go forward with immense rapidity. The waste which is held within the region is, therefore, largely held as soil, on the moderate slopes, and not as detritus, and upon any climatic change which shall diminish the effectiveness of the vegetative covering is liable to be swept away with geological suddenness as a flood of clay, sand, and gravel.

On the side of the mountains possessing a subarid or arid climate, the waste is swept away as soon as disintegration frees it from the rock, and is largely stored in interior basins or on piedmont slopes. This material adjacent to the mountains is but little decomposed, has less true clay, and on the whole is coarser than the similarly situated waste of milder or more pluvial climates. As examples

[1] E. Huntington, *Explorations in Turkestan, with an Account of the Basin of Eastern Persia and Sisten*, Carnegie Institution Publications, No. 26, 1905, p. 269.

[2] E. W. Hilgard, *Soils of the Humid and Arid Regions*, p. 413, 1906.

may be cited the coalescent gravel fans of Persia forming the "skirts of the mountains," and the detrital slopes of the mountains in New Mexico and Arizona.

As a description of the character of erosion in the heart of the desert mountain region of Arizona may be cited a paragraph by Ransome, who, writing of the Globe copper district, says:

> With the exception of the timbered slopes of the Pinal Mountains, and a few alluvial areas along the main arroyos, the surface of the region is almost destitute of soil. The scanty shrubbery, and the sparse grass and herbage which spring up with wonderful rapidity after the rains, are insufficient to prevent such soil as may form from being quickly washed away. The humus acids, which in moister climates and beneath the covering of soil aid in rock decay, have in this region little opportunity to form or to attack the rocks. The latter crumble or flake under the influence of sharp atmospheric changes, and these fragments are rapidly carried into the valleys. The granitic masses crumble into particles of quartz, flakes of mica, and angular fragments or crystals of comparatively fresh feldspar. The rains acting on this disintegrated material soon wash it down to the larger streams, which carry off the quartz and mica. The larger fragments of feldspar often build up alluvial fans at the mouths of the small ravines heading in a granitic area, and such fans are remarkable for the purity and freshness of the feldspathic material which composes them, the numerous cleavage faces flashing brightly in the sun. Excellent examples of these fans were observed along Pinto Creek, north of Horrell's west ranch. They are evidently transient phenomena, accumulating until an exceptionally wet season causes Pinto Creek to rise and sweep them away.[1]

The rainfall varies in adjacent parts of this region and in successive years, the amounts ranging from 11 to 20 inches per year, a considerable proportion falling as rain during the sudden and violent downpours which are common in July and August.[2]

Upon a climatic change causing more voluminous streams to flow across the piedmont slopes or drain the interior basins, the stream profile for equilibrium is altered, a large amount of coarse, unleached, and incoherent waste may be quickly swept downstream, even to the delta, and be deposited either upon its upper surface as partly subaerial products, or swept to the front, building the delta farther seaward.

[1] *Geology of the Globe Copper District, Arizona,* Professional Paper No. 12, U. S. Geological Survey, 1903, p. 21.

[2] *Op. cit.*, p. 20.

MATURE TOPOGRAPHY AND VARIOUS CLIMATES

Upon a mountain region becoming mature, its lower summits and rounded slopes exercise less effect upon the climate, which now becomes less accentuated and contrasted in nearby regions, and the rainfall may extend for some distance beyond the crest line. Broad extents of continental lands are here more important as modifiers of the climates natural to the several zones. There is still a marked relation in detail, however, between the climate and the surface. The problem has been studied in Persia with particular reference to climate by Huntington, who states:

A prominent characteristic of the mature mountains of Persia is their nakedness, roughness, and sterility. In a young country it is to be expected that there shall be large areas of naked rock, but in a mature country, if the rainfall is abundant, most of the surface, except the immediate valley sides, is graded, and thus covered more or less deeply with soil. Eastern Persia, however, is so arid that the ordinary state of affairs is reversed. All the mountains, whether young or mature, are characterized by nakedness. Graded slopes are not a feature of maturity in an arid climate.[1]

The valleys and basins are deeply filled with waste and the area of exposed rock is not, however, so great as during the period of youth.

The differences in the chemical and physical composition and the place of storage of the rock waste of arid and well-watered mountains become emphasized with maturity. This heightened contrast is due to the larger and deeper mantle of rock waste exposed to the particular climatic influences and moving more leisurely from its original source to the reach of the streams. The contrast in kind of products due to the climatic difference is well brought out by Hilgard,[2] who points out that—

since kaolinization is also a process of hydration, the presence of water must greatly influence its intensity, and especially the subsequent formation of colloidal clay; so that rocks forming clay soils in the region of summer rains may in the arid regions form merely pulverulent soil materials. Many striking examples of these differences may be observed, e. g., in comparing the outcome of the weathering of granitic rocks in the southern Alleghenies with that of the same rocks in the Rocky Mountains and westward, especially in California and Arizona.

[1] *Explorations in Turkestan,* Carnegie Institution Publications, No. 26, 1905, pp. 247, 248.

[2] *Soils,* 1906, p. 47.

The sharpness of the ridges of the Sierra Madre, and the roughness of the hard granitic surfaces, contrast sharply with the rounded ranges formed by the "rotten" granites of the Atlantic slope, where sound, unaltered rock can sometimes not be found at a less depth than forty feet; while at the foot of the Sierra Madre ridges, thick beds of sharp, fresh granitic sand, too open and pervious to serve as soils, cover the upper slopes and the "washes" of the streams, causing the latter to sink out of sight. A general discussion of the kinds of soils formed from the various rocks must, therefore, take these differences into due consideration.

The lack of decomposition and the dominance of disintegration in desert regions, giving rise to fresh and unweathered sands, have also been emphasized by Walther, who shows that insolation breaks up crystalline rocks into a rubbish of crystals scarcely altered chemically.[1] Merrill and others have abundantly confirmed this as a principle dominating the production of rock waste in arid climates.

OLD TOPOGRAPHY AND VARIOUS CLIMATES

Regions topographically old are of lessened importance from the view-point of the mechanical sediments of running water, but little waste being contributed to the deltas and the seas and the conditions for limestone formation approaching close to the shores. In the old age of the humid region the blanket of decomposed rock becomes universal and increased in thickness, giving rise upon erosion to fine-grained and well-decomposed silts. In the arid regions, on the contrary, the waste in the rock basins diminishes in thickness through wind and water erosion and the desert becomes finally covered with a thin gravelly or sandy mantle still characterized by lack of decomposition. In the old age of arid regions, as shown by Passarge, wind erosion becomes increasingly more important than water erosion, since the water loses its force upon the flat desert surface, while the action of the wind does not diminish in intensity. The products of erosion in old age, therefore, are chiefly wind-borne loess and dune sand, possessing distinctive qualities and a different distribution from sediments of fluvial and pluvial origin.

Relations of Temperature and Topography to Erosion

EFFECTS OF TEMPERATURE VARIATIONS ON VEGETATION AND SOIL RETENTION

Besides the relations dependent upon rainfall, those dependent upon temperature may also be considered. In general, increased cold

[1] *Einleitung in die Geologie*, 1893–94, pp. 546–47.

with stable precipitation but without glaciation has been considered geologically equivalent to stable temperature and increased rainfall, since the evaporation is decreased and the run-off consequently increased, but an analysis of the problem would appear to show that in its ultimate stratigraphic effects it is much more complex than this, a complexity which has been recognized possibly for the first time by Chamberlin and Salisbury,[1] who state:

The cold climate probably affected erosion, and therefore deposition in another way, for the reduction of temperature was probably attended by a reduction of vegetation, and any diminution of vegetation must have reflected itself in increased erosion. The reduction of vegetation was probably greatest just where erosion was most readily stimulated, namely, in the higher altitudes. The importance of this consideration has perhaps not been duly considered.

On the other hand, a marked rise in mean annual temperature without change in precipitation will, in a region already under optimum climatic conditions for vegetation, be equivalent to a movement toward aridity. This is seen on comparing tropical deserts with those of the temperate zone, where in the former a precipitation twice as great may not prevent the existence of a similar aridity. The results in the decrease of the vegetative hold upon the soil and a consequent increased erosion, provided there is sufficient run-off to remove the rock waste, will be similar to the results of a change toward unfavorable cold.

It may be stated in conclusion, therefore, that any marked variation of temperature away from that which in combination with the rainfall gives the optimum conditions for vegetable growth will result in a loosening of the soil and a corresponding increase in the rate of erosion. The diminished area of rock covered by the soil and the thinner covering where it does exist will, in combination with the lessened amount of organic matter, result in an increase of disintegration and a relative diminution of rock decay.

EFFECTS OF INCREASED COLD

On frost action and erosion.—Not only is the balance of the vegetative covering to erosive power disturbed, but during periods of increased cold the frost action over exposed rock surfaces becomes more energetic. Its intensity at high mountain elevations or in high

[1] *Geology*, Vol. III, 1906, p. 453.

latitudes has been pointed out by Walther,[1] by Russell,[2] by Merrill,[3] and others, and reliance upon this action has been employed by Oldham to reach the conclusion as to the existence of a period of cold, but one not attended by glaciation during the deposition of the Panchet group, early Mesozoic of India.[4]

It has been thought by some that perhaps a rigorous winter climate does not promote corresponding disintegration, since during a considerable portion of the year there may be no thaw. Observation seems to indicate, however, that with increase of altitude or latitude the results of frost action become progressively more pronounced. The explanation is apparently to be found in the fact that although surface melting and refreezing may be absent, frost action is at such times penetrating constantly deeper. The period of daily freezing and thawing will in this case occur at the two ends of the winter season instead of the middle and on account of the greater daily insolation and nocturnal radiation the effects may be as pronounced as during a somewhat longer period near the winter solstice.

If the cold becomes so great, however, as to result in a perpetually frozen substratum, the disintegrative action will presumably become less instead of greater, but such a condition does not exist at present except under polar climates. It is not one which would, so far as known, become widespread even at times of glaciation, and is the consequence of a climatic extreme which need hardly be considered.

The effects of increased cold in regions of no glaciation must consequently be either one of two kinds, depending upon whether frost action or snowfall is increased: frost tending to make more rock waste; snow tending to prevent frost action and by its melting to carry waste away.

In climates possessing but little snowfall, increased variations of temperature and increased frost action will be the most marked results of a change to a colder climate. In regions of exposed rock

[1] *Einleitung in die Geologie*, 1893–94, p. 559.

[2] *Notes on the Surface Geology of Alaska*, Bulletin of the Geological Society of America, Vol. I, 1890, pp. 133–37.

[3] *Disintegration and Decomposition of Diabase at Medford, Mass.*, Bulletin of the Geological Society of America, Vol. VII, 1896, pp. 349–62.

[4] *A Manual of the Geology of India: Stratigraphical and Structural Geology*, 2d ed., 1893, p. 201.

surfaces, and therefore typically in rugged mountainous regions, this must result in a more rapid disintegration of the naked rock masses and an increased supply of talus to the streams. Under the small precipitation postulated, however, the streams will be only slightly increased in volume by the decreased evaporation, and presumably not able to carry away the excess of load. The weakening of the vegetative covering over the soil-covered slopes would work to the same end, but in a desert region this factor would be absent. The tendency of the increased disintegration would be to build up piedmont slopes, whose rate of growth would diminish or even cease upon a return to less rigorous winters. The effects of increased cold in many cases may, therefore, disturb the balance of erosion to transportation, in the same way as a change toward more marked aridity without increased cold.

The Gila conglomerate of Arizona.[1]—As an example of a Pleistocene formation which it was thought might be due to some such cause, the writer has examined the literature on the Gila conglomerate of Arizona, a formation now dissected in many places to the depth of a thousand feet and attaining its maximum development in the upper portions of the valleys of New Mexico, Arizona, and southern California. The specific nature of the climatic or tectonic changes which could have resulted in its production does not seem to have been fully discussed, the only definite opinion expressed being that of Lee that in so far as climate was a factor in the accumulation of this upland débris in southern California and Arizona, it was in the nature of a desiccation.[2] Others consider that their Pleistocene age and the finding in New Mexico of contemporaneous elephant, horse, and tapir bones are an indication of the accumulation of similar New Mexican deposits during an epoch of moist climate in the early Pleistocene.[3]

An examination of the literature showed that the relations of the two divisions of the Gila conglomerate, the volumes and relative

[1] The writer hopes to publish a fuller discussion of this subject than can be given here.

[2] "Underground Waters of Salt River Valley, Arizona," *Water Supply and Irrigation Paper No. 136*, U. S. Geological Survey, 1905, p. 115.

[3] George B. Richardson, *Science*, New Series, Vol. XXV, 1907, p. 32.

ages of each, corresponded with the two epochs of glaciation which were pronounced in Utah and Nevada and the two periods of expansion of Lakes Bonneville and Lahontan. This taken in consideration with the place of deposit of the gravels, in the upper portions of the river valleys, leads to the view that the Gila conglomerate originated from an increase in the ratio of erosion to transportation, due to the severe cold and consequent frost action of the glacial times, without a correspondingly large increase, in this arid region, of precipitation. The ultimate cause of the accumulation under this view was greater cold and not a desiccation, since the precipitation was doubtless somewhat increased as shown by the mammalian bones. Any conclusion in regard to the exact cause and correlation is, however, of minor importance in comparison with the broader one that the deposit is due to climatic causes rather than those of a local or regional tectonic nature. If this conclusion be well founded it is seen that in this desert region with mountainous topography climatic changes have been a sufficient cause to result in the laying-down over wide areas adjacent to the higher mountains of a conglomerate formation largely over a thousand feet in thickness, justifying the statement that climatic changes may result in sedimentary formations as important as those due to tectonic or oceanic causes.

Effects of increased cold on snowfall and erosion.—In regions where the increased cold results in the precipitation of snow which previously had fallen as rain, frost action and also chemical action may not be increased, and the chief results of the spring floods resulting from the melting snow may be an increase of transportative power. The protecting power of snow against both disintegrating and decomposing agencies has been cited by Salisbury as probably contributing to the fresh and unweathered appearance of the Wisconsin drift of the Bighorn Mountains when compared with that of the continental interior.[1]

In mountainous regions such as the Sierras, where the snowfall is markedly greater at the higher elevations, the floods produced by the spring melting are not proportionately augmented upon reaching the lowlands, and deposition of the excess load is to be expected

[1] *Geology of the Bighorn Mountains*, Professional Paper 51, U. S. Geological Survey, 1906, p. 87.

upon the piedmont slopes. The same is found to be true on the eastern slopes of the southern Andes on portions of which aggradation is now in active progress. An increased snowfall without actual glaciation, especially if it takes the place of what had previously fallen as rain, may therefore result in the waste being carried farther before deposition, accompanied by a dissection of the upper portion of the piedmont slope, the results being opposite to those of increased frost action. In regions of less elevation, however, the rainfall and snowfall are nearly the same upon upland and lowland, the volumes of the streams are increased as they flow toward the sea, the sediment once picked up is carried through by the river, and as a result of increased snowfall an increased erosion may take place without the tendency to aggradation in the middle portions of the streams. Such an effect is in many ways equivalent to a change toward a more voluminous or at least more concentrated regional rainfall. In the preceding statements snow and frost action have been considered separately. In nature, however, there may be various combinations of these agencies. Increased cold may lessen the hold of the vegetation on the soil, the latter, saturated in the spring with snow water, may be more rapidly removed, and an opportunity be given for increased frost action. Consequently, while a greater amount of sediment may be carried through to the lower portions of the river system, aggradation may yet take place to some extent in the upper portions. Some such change of relations seems to have occurred during glacial times over certain regions outside of the limits of glaciation, since terraces and fans of glacial age characterize the upper portions of many river systems. These conditions find their maximum development at the present time in the subglacial polar or mountain climates. The subject has been discussed by J. G. Andersson,[1] who shows that the regolith, becoming saturated with snow water, creeps slowly but bodily down even the gentler slopes. The production of new waste is chiefly dependent upon frost action; so that the two results of a lowering of temperature co-operate and it is not practicable clearly to separate them. The Gila conglomerate, however, on account of the short distance which the bulk of the material was transported,

[1] "Solifluction, a Component of Subaerial Denudation," *Journal of Geology*, Vol. XIV, 1906, pp. 91–112.

and the lack of evidence of highly increased precipitation at the time would seem to be due more largely to frost action.

In conclusion it would appear that where the chief effect of increased cold is an increase of snowfall the change results in an increase in the ratio of transportation to erosion, extending to the limits of such increased snowfall, and not as in the case of increased frost action to an increase of erosion over transportation. The absolute value of both erosion and transportation may increase in both cases.

EFFECTS OF INCREASED HEAT ON ROCK DISINTEGRATION AND DECAY

It is seen that rock disintegration or physical weathering is at a maximum in regions of exposed rock surfaces, while rock decay is pronounced, on the contrary, where the solid rock is protected from physical changes by the interposition of a layer of soil. The former conditions of bare surfaces are found in mountainous regions, where the steep slopes prevent the retention of soil; or in the deserts, where the absence of ground-water prevents either the formation of an effective vegetable covering or the carrying-forward of the chemical processes of rock decay. The contrary conditions of soil-mantled surface exist where the slopes are moderate or the presence of ground-water gives rise to a vegetable covering sufficient to hold the soil and diminish erosion of its upper surface to a rate equal to that at which decay contributes to the lower strata of the soil. In a climate where rock decay operates strongly there thus arises a very deep soil, partially protecting the deeply buried solid rock from further decomposition and slowing down the rate of decay till it equals the rate of surface ablation, hindered in turn by the luxuriant vegetation also existing in such a region. Both the topographic and climatic factors are thus seen to be fundamental in the result. Under the present topic it is desired to note what effects a climatic variation toward an increase of temperature will have upon these processes of physical and chemical rock destruction which necessarily precede subaerial denudation and are the supplying agents for the diverse materials of sedimentary formations.

Effects on rock disintegration.—To produce rock disintegration a high temperature is not necessary but diurnal or hourly variations

of temperature must occur, and the effects will be proportional to the magnitude and rapidity of these changes. As causes tending to magnify these rapid temperature variations may be cited: first, a short transmission of the sun's rays through the atmosphere, implying a thin atmosphere as found on mountains and high plateaus or a high altitude of the sun; second, surfaces at right angles or nearly so to the sun's rays; third, a lack of clouds or of water vapor and to a lesser extent a lack of carbon dioxide in the atmosphere, the former characteristic of continental interiors, the latter of certain geological epochs; fourth, a high value of the solar radiation will increase the disintegrative effects by producing more rapid heating and, as a result of the higher surface temperatures attained, a more rapid cooling when the rock surface passes into shade. Sudden dashes of rain, such as are characteristic of arid and semiarid regions, also operate as a powerful cause of rock disintegration.

To take up these in order: Angot has shown that, although at the summer solstice the quantity of heat received per day at the poles is greater than at the equator, if 0.2 of the solar radiation is absorbed by passing vertically through the atmosphere, then at the poles less reaches the surface of the ground than at the equator.[1] The constancy of the polar daylight at the solstice tends also to prevent rapid temperature changes.

The daily *maximum* insolation of the surface is found to be not far from a constant quantity up to lat. 60, with a maximum at from 30 to 40 degrees. In the higher latitudes, however, this maximum insolation occurring at the summer solstice lasts for but a short time, sinking in the winter to an insignificant quantity. It may be stated then on theoretical grounds that, other conditions being favorable, thermal disintegration may operate strongly to the limits of the polar zones, but that the aggregate effect varies approximately with the latitude, reaching a maximum at the equator and disappearing as an important factor on the polar circles.

Mountain elevations exert an influence upon insolation as important as latitude, a marked difference being noted between the air and

[1] Alfred Angot, "Recherches théorétiques sur la distribution de la chaleur à la surface du Globe," *Ann. bur. central met. de France*, Tome I, 1883, Paris, 1885, B 121–B 169.

ground temperatures, the intensity of solar radiation being 26 per cent. greater on the summit of Mount Blanc than at Paris.[1] Steep rock faces favoring perpendicular action by the sun become of increasing influence in the higher portions of the temperate zones and may even in the arctic, as in Greenland, give a local importance to insolation as a cause of rock destruction, von Drygalski having observed a temperature difference of 20° C. between the air and rock surface.[2]

In regard to the influence of atmospheric composition, it is known that water vapor is the most efficient absorbing medium of the solar heat and also prevents the rapid re-radiation of that part absorbed by the earth's surface, preventing by both means high temperature differences. Clouds also act both by preventing solar radiation from reaching the ground and checking the escape of that already absorbed. These direct effects, taken also in connection with the indirect effects of the presence of water through vegetation, limit insolation as a mode of rock destruction to mountain and desert regions.

Finally, in considering the geological relations of climates to erosion, possible variations of the solar constant of radiation must be considered, an increased intensity of radiation, as previously pointed out, increasing insolative rock disintegration, but only within the limits given by the other conditions. The chief effects of such solar variation would therefore be indirect, by changing the vapor content and cloudiness of the atmosphere, both in geographic location and amount. There are strong reasons for believing, though perhaps hardly yet demonstrated, that an increase in solar radiation would result not only in a slight increase in the mean annual temperature of the earth but also in areal increase of those portions of continental interiors subject to arid and subarid climates. At the same time it is probable that an expansion of the trade-wind belts into somewhat higher latitudes would occur. Certain other regions would also be marked by heavier rainfalls. On the whole, the result would be an accentuation of climates and a marked increase in insolation as a cause of rock disintegration.

In conclusion, it is seen that the control of insolative rock disintegration is largely geographic, being favored in past times by increase

[1] Julius Hann, *Handbook of Climatology*, transl. by R. de C. Ward, p. 233.

[2] *Verdhältniss Geschichte für Erdkunde*, Berlin, 1891, p. 457.

of area and unification of the continental surfaces, giving rise to largely increased areas of continental climates. The indirect action of the sun, however, as just pointed out, is probably an equally potent factor.

According to Murray, one-fifth of the land surface is now desert, having no drainage to the sea.[1] Over this region insolation and eolian abrasion are the chief modes of rock destruction. It may well have happened that in past times of wide epicontinental seas with moist atmospheres and world-wide equable climates, or in times of cold and glaciation, insolation may have sunk to half its present importance as a mode of rock destruction. On the other hand, times of broadened land areas, especially if occurring simultaneously with high solar radiation, may have increased the desert areas beyond their present extent, or at least shifted their limits into higher latitudes, giving rise to peculiar characteristics, such as distinguish particularly the Triassic formations.

The first factor in the acquisition of any such distinctive characters of sediments must depend upon the mode by which the parent rock masses are destroyed. In this respect frost action and insolation act alike, producing rock disintegration without rock decay, both most efficient in regions without heavy precipitation and accentuated by climatic movements away from a temperate condition, but in opposite directions. The subsequent effects of these opposite climates upon the sediments are, however, widely different, as will be made evident on other pages.

A conclusion of some stratigraphic importance is that, if the Gila conglomerate has been correctly interpreted, it is seen that in desert mountains strongly increased frost action with slightly decreased insolation of glacial times is more effective in supplying waste than the present slightly increased insolation with much weakened frost action.

Effects of increased heat on rock decay.—Rock decay implies the presence of water, since it is only in its presence that not only hydration but carbonation and oxidation of mineral substances can take place. The problem, then, is in regard to the influence of temperature in promoting rock decay in regions of moist climate. In regard to this von Richthofen is one of the first to observe that—

[1] "Origin and Character of the Sahara," *Science*, Vol. XVI (1890), p. 106.

weathering in fact becomes in large measure a climatic phenomenon. In moist and hot regions it is accomplished easily and rapidly; in hot and dry regions it seems to play an unimportant part, and where high degrees of cold prevail even an abundance of water is unable to produce it in any but an insignificant amount. Beneath the ever-moist moss cushions of Finland and the northern Ural, granite shows undecomposed surfaces.[1]

Russell, from observations in the southern hemisphere, reaches the same conclusions, his statements being as follows:

I may remark from observation that in the Kerguelen and Crozet Islands, in the South Indian Ocean, where a cold, humid climate prevails, and where not only forests but arborescent growths of every description are wanting, there is but little soil, and nothing approaching terra rossa is to be seen. These islands are formed, probably throughout, of dark basaltic rocks, rich in iron, which under more favorable conditions would yield a deep layer of ferruginous soil. Contrast with the Kerguelen Islands others of similar origin in the tropics, as the Samoan Islands, for example. On Kerguelen the highest vegetation is a bitter cabbage which grows mostly in sheltered places along the coast, where it is surrounded with matted ferns and tussocks of moss. The landscape, even on the exceptional days of sunshine, is dark, silent, and gloomy. Among navigators this island is called, not unjustly, the "Land of Desolation." In the Samoan Islands the rank luxuriance of tropical vegetation imparts to the land when seen from the ocean the deep tint of malachite. Wherever the bare earth appears it gleams forth through the overshadowing boughs with a brilliancy that is enhanced by contrast and gives a dash of Pompeian red to the picture of tropical beauty. The soil is deep and rich, and, as in Bermuda, must have been derived entirely from the decay of the rocks forming the islands, which in this case, however, are basaltic, and agree in many ways with the rocks forming the Kerguelen Islands.

The contrast between the present condition of the Kerguelen Islands and that of the Samoan Islands has resulted from differences in climatic conditions. This conclusion would have to be modified, perhaps, should it be found that the former had recently been glaciated. There are abundant observations to show, however, that, in general, islands below latitude 50° south, where winter is almost continuous, are desolate, uninhabitable wilds, and that forty degrees nearer the equator, where perpetual summer reigns, lands formed of nearly identical rock have suffered deep decay and are covered with a rich ferruginous soil, which supports a varied and luxuriant tropical flora.[2]

That rock decay may take place to some extent in cold climates and is frequently absent because of glaciation is indicated by the observa-

[1] *Führer für Forschungsreisende*, Berlin, 1886, p. 100.

[2] *Subaerial Decay of Rocks and Origin of the Red Color of Certain Formations*, Bulletin 52, U. S. Geological Survey, pp. 30, 31, 1889.

tions of Chamberlin in Greenland and of others in Alaska cited by Merrill.[1] Observation and theory combine, however, in pointing to the greater dominance of the forces of rock decay in warmer pluvial climates and especially in the rainy portion of the torrid zone, the natural activity of the warmer waters being further increased by the organic acids supplied by the large amount of decaying vegetable matter, giving rise to a mantle of rock waste of maximum thickness, thoroughly hydrated and leached by the heavy periodic rains, and thoroughly oxidized by the intervening seasons of dryness. The result is the formation of the red or pink laterite soils of the tropics, and the characteristic red alluvium of the rivers,[2] alluvium poor in soluble constituents.[3]

The effect of moderate cold, such as characterizes the winters of the middle temperate zone, appears to have slight effect upon the erosion of regions in topographic maturity, save that the melting of the winter's snow gives a temporarily higher flood and greater erosive power than would otherwise occur. The summer's heat being less prolonged and intense, gives rise also to less intense oxidation of the soil and less dehydration of the iron oxide, yellows and browns prevailing as soil colors and yellows or grays characterizing the river silts in place of the browns or reds of tropical rivers.

In conclusion, therefore, it may be stated that an increase of temperature away from a temperate mean in regions of heavy rainfall will result in increased rock decay and decreased frost action, and in the opposite characteristics in the case of a temperature decrease. Either variation away from a climatic mean would therefore result in an increase of rock destruction, but of opposite kinds. It is not known, however, but that in the case of an increase of temperature with an abundant rainfall the hold of the vegetation upon the soil may be increased to such an extent as to neutralize the tendency toward more rapid production of rock waste by decay. A close comparative study of valley forms of similar age in the middle and southern Appalachian states in similar rocks would tend to throw light on this problem and show if *erosion* as distinguished from *rock decay*

[1] *Rocks, Rock-weathering, and Soils*, 1897, pp. 278, 279.

[2] Walther, *Einleitung in die Geologie*, p. 815.

[3] Hilgard, *Soils*, 1906, chap. xxi.

is faster in the warmer or cooler climate. In any case, it is evident from the preceding discussion that a series of climatic oscillations involving merely temperature changes would find record in the varying kind and rate of erosion and consequent sedimentation in regions either where this climatic change was between cold and temperate or between temperate and torrid limits.

Separation of the Topographic and Climatic Factors

As previously stated, under the relations of rainfall and topography to erosion, young, mountainous topography not only gives rise to rapid erosion, but accentuates climatic contrasts, so that a marked distinction may still have opportunity to become developed between the products of erosion of humid and arid mountain regions. The extent to which this is true may be seen by comparing the alluvium of the Rio Grande with that of the Missouri-Mississippi system, where in silts of the same degree of fineness that from the arid region shows a much higher ratio of soluble constituents.[1] The researches of the geologists of India indicate the same contrast between the alluvium of the Indo-Gangetic plain and that of the Brahmapootra in southern Assam.[2] In these examples the material is derived from regions of high relief and rapid erosion. Gravels or cobbles may be deposited under such circumstances nearer the sources, but the production of the conglomerate has involved initial rock-breaking and the production of a considerable quantity of fine material which may occur as a matrix or as separate deposits of clay or silt. These finer materials, as stated, have distinctive characters in each strongly marked climatic province.

It is concluded, therefore, that an examination of the character of the matrix or associated fine beds is of importance in determining the climatic conditions attending the origin of a terrestrial conglomerate or sandstone. This conclusion may be illustrated by contrasting the red sandstones and shales, occasionally conglomeratic, of the Connecticut Valley, with the predominantly gray conglomerates and black shales of the Carboniferous basin of Rhode Island; the two regions being separated by less than fifty miles, and both containing sediments of rather local origin. There are strong evidences in

[1] Hilgard, *Soils*, 1906, pp. 368, 378. [2] Hilgard, *op. cit.*, p. 413.

each case indicating subaerial origin, much of which however is not published. The dominant red color of the whole of the Triassic formation, considered in connection with its feldspathic sandstones indicative of the kind of erosion, mud-cracked shales, disseminated gypsum, and calcite, indicative of conditions of sedimentation, point on the one hand to a subarid climate, while the carbonaceous and leached shales of the Rhode Island coal measures indicate a climate markedly pluvial and cool. It is to be noted that in the Rhode Island basin arkose conglomerates of local origin grade into carbonaceous shales.[1] The conglomerates are extremely abundant and except in the Wamsutta red beds possess a light-gray matrix, while the shales are usually darker in color. Thus the conclusion previously stated is emphasized, that in humid climates, even in regions of rapid denudation and deposit, the finer materials eroded will show greater decomposition and leaching than material of similar fineness, even when derived more slowly from the erosion of surfaces of moderate relief in arid climates. The character of the fine fluviatile or wash detritus *in the region of its origin* may, therefore, be taken as an index of climate. The size or abundance of the coarser material on the other hand forms a measure of the rapidity of erosion, and roughly of the degree of topographic relief. Where the matrix or the form of the cobbles indicates, in association with other evidence, the presence of arid or cold climates, however, disintegration dominates over decomposition, and conglomerates in the region of erosion must be correspondingly coarser and more abundant to indicate the same relief as that of a more rainy region. In rivers sufficiently large so that the erosion and deposition occur in different climatic zones only the finer débris will reach the delta. The chief effect of rugged topography in that case is found in the quantity of sediment and, as will be further discussed in Part III under the topic of the "Effects of Fluviatile Transportation," the evidence as to the climate of the *soucre* becomes more obscure the farther the alluvium is carried.

Separation of Tectonic and Climatic Oscillations

A full discussion of this topic involves the effects of tectonic and climatic movements upon both transportation and deposition as well

[1] A. S. Packard, "View of the Carboniferous Fauna of the Narragansett Basin," *Proceedings of the American Academy*, Vol. XXXV, 1900, p. 405.

as erosion, subjects which are treated in the following chapters. A partial statement, in so far as erosion is involved, may, however, be made at this place.

It has been seen that climatic variations are potent causes of changes both in the absolute rate of erosion and in the ratio of erosion to the forces removing the waste. While erosion is dependent for its existence upon initial tectonic movements, it has been seen that its varying rate is as dependent upon climatic variations as upon those secondary crustal movements by which occur further uplift or depression or distortion.

Criteria for the distinction of these tectonic and climatic factors are discussed by Davis, in so far as erosion at the headwaters and aggradation of the middle slopes are concerned, and the conclusion is reached that in general the terracing in Central Turkestan seems to be due to climatic variation.[1] The recognition of the importance of climate in building river terraces is in fact a feature in this volume in both the papers of Davis and Huntington. It is only necessary in consequence to summarize briefly certain points which distinguish the upstream terraces built as a result of climatic from those formed by tectonic oscillations. First, the development of terraces on the upper portions of the streams, terraces which die out lower down in the valleys, implies a change in the stream gradients not due to a raising or lowering of the mouth. Regional uplift or depression is excluded in this way. Such a change in gradient in the upper portion of a stream may be due to a local uplift, to a regional warping or a change in the ratio of erosion to transportation brought about by a climatic change. Second, the universality of an epoch of aggradation or degradation in all of the streams of a region is a strong indication of a climatic change, since, as Davis has noted, the crustal bendings necessary to rejuvenate all streams flowing in various directions and finally frequently to bring them back to the initial profile would be extremely complicated and involve an adjustment of subsurface movement to detailed surface form such as is not known to occur and is in fact unthinkable. Although a general similarity in the action of various streams would be expected to occur as a result of climatic

[1] *Explorations in Turkestan,* Publications of the Carnegie Institution, No. 26, 1905, p. 203.

change, this could not be carried down to all details; since it is seen, for instance, that in Arizona, Queen Creek at the present time begins to deposit sediment immediately upon leaving the mountains, while the much larger Gila flowing parallel and but eleven miles to the south flows through the plain as far as Florence in a well-marked valley. In this respect it is to be expected that various streams will behave somewhat after the manner of glaciers, where each responds in its own time and to varying degrees to periods of increased or decreased precipitation of snow. Third, while extremely contrasted climates may leave many distinctive marks in the character of the matrix of even locally transported materials, as shown in the contrast of the Carboniferous of Rhode Island to the Triassic of Connecticut, minor climatic fluctuations cannot be expected to be so recorded. As evidence of such variations, therefore, disturbance of the stream gradient and changes in the coarseness of the detritus must be looked for.

CONCLUSIONS ON RELATIONS OF CLIMATE AND EROSION

The relative rates of erosion in desert, tropical, and polar climates is a subject upon which there is much diversity of opinion, as Merrill has shown.[1] The difficulties are largely due to the differences in kind of erosion between hot and cold, and arid and rainy climates. The usual geographic remoteness of these extreme types from each other further increases the difficulty. Doubtful conclusions have also sometimes been founded upon the quantities of rock waste present, it being assumed that where rock is deeply decayed, as in the rainy belts of the tropics, it now weathers and erodes rapidly, whereas, on the contrary, the deep regolith may check further decay and the matted vegetation retard the erosion of the surface. Or a traveler may be impressed with the naked mountains and waste-filled valleys of a desert region and conclude that here rock destruction progresses more rapidly than elsewhere on the earth.

A more satisfactory method than that of founding conclusions on quantitative estimates from a few unlike localities is to compare the decay and erosion of unlike climates not with each other but with a third term. For example, the subaerial erosion of arid and rainy regions may be compared with the marine erosion of their coasts, a

[1] *Rocks, Rock-weathering, and Soils*, 1897, pp. 278–85.

common third term, while the influence of warm and cold climates upon erosion may be studied by comparing the erosional rate of glacial times with that of the same regions at present, here the common third term being the topography. This has already been done under the topic of the effects of increased cold.

Turning to the ratio of erosion in arid and rainy climates, as compared with marine denudation, it must be noted that a conclusion should be founded on the average of many instances rather than on a few, since in each the age of the cycle, the attitude and strength of the rock masses, and the strength of the marine erosion will vary. The present discussion must therefore be considered as merely tentative. Very different views have been developed in Great Britain and the United States as to the marine or subaerial production of uplifted and dissected peneplains of Cretaceous and Tertiary age which border the continents, but the growth of knowledge in regard to the capacity of subaerial denudation first in America and more recently in England has given rise to the belief that these are mostly due to subaerial erosion, views confirmed by the application of such criteria as can be applied.[1] In general in rainy climates the rivers are observed to sink rapidly toward base level upon an uplift of the land, to open out interior plains in soft formations, and to dissect deeply the hard ones, while the sea, compelled to work on the outlying formations whether they be hard or soft, cuts inland over a comparatively small area and with increasing difficulty. The problem in such climates is to find good and unquestioned examples of elevated plains of marine denudation comparable to the elevated plains of subaerial origin.

Along the arid coasts of the world very different conditions are, however, found to prevail. To cite examples:

While the Patagonian plains have an altitude of some three thousand feet at the base of the Andes, they slope very gently to the eastward, and at a distance of some fifty miles from the Atlantic coast, their elevation is more rapidly decreased by a series of escarpments or terrace-like slopes, which face to the eastward and terminate a succession of level plains, decreasing in altitude as one passes from the interior to the coast and finally ending in the lowermost, which, with an average altitude of some three hundred and fifty feet, extends almost uninterruptedly along

[1] W. M. Davis, "Plains of Marine and Subaerial Denudation," *Bulletin of the Geological Society of America*, Vol. VII, 1895, pp. 377–98.

the entire eastern shore, terminating abruptly in the lofty and precipitous cliffs, which for a thousand miles constitute the predominant feature of this coast.

In addition to the characters described above, there may be mentioned as among the more important features of these plains a series of deep transverse valleys that extend from the Andes to the Atlantic. These are all true valleys of erosion, and for the most part they are still occupied by considerable streams.[1]

The prominence of these cliffs indicates the extent to which the waves have planed inland, beginning a new and lower cut upon each uplift of the land. The inadequacy of subaerial denudation in this semiarid climate, with less than ten inches annual rainfall, is indicated by the presence, except in the few river valleys, of the shingle formation left by the retreat of the sea and the fact that the large river valleys are such as derive their waters from the Andes. In more rainy regions the almost level and porous deposits left upon a retreat of the sea also resist rain erosion in the interstream areas for considerable periods of time, but in such regions there is much local drainage and the development of a network of valleys which upon a pronounced uplift permit a rapid erosion.

Along the southwestern coast of Australia for a distance of seven hundred miles the land is terminated by a line of cliffs more than five hundred feet in height unbroken by any stream course and facing a shallow sea which in the Great Australian Bight extends to one hundred and fifty miles from land before attaining a depth of one hundred fathoms. The rainfall is here not over ten inches per year. Such lofty and unbroken walls indicating the dominance of marine over subaerial erosion, it would seem impossible to match in more generously watered regions of theworld; such cliffs as those of Norway and Scotland being cut through on the contrary by valleys of erosion besides forming the front of mountain regions and therefore not necessarily implying a wide horizontal cut for their formation.

The preceding discussion has turned upon the slowness of subaerial erosion in arid climates when acting upon more or less horizontal and débris-mantled formations. An indication of the relative slowness of deflation may also be obtained from southern California and its adjacent islands by noting the remarkable freshness of the naked granite rocks and the sharpness of the post-Pliocene elevated sea-

[1] J. B. Hatcher, *Princeton Patagonia Expeditions*, Vol. I, pp. 214, 215, 1903.

cut cliffs reaching an elevation on San Clemente of 1,320 feet. These according to Lawson are the most remarkable and most magnificent examples of this type of topography which it has ever been his good fortune to behold. He further remarks that such features one might expect to find on a planet, which after their formation, had become stripped of its atmosphere.[1] Similar terraces are found on the coast of northern California, and Lawson regards the whole as due to epeirogenic movement which he considers as sufficiently simultaneous to inaugurate a new geomorphic cycle which is in a nearly uniform state of advancement all along the coast.[2] Under the rainy climate of the coast of northern California, but especially of Oregon, these raised beaches are still conspicuous; but it is noteworthy that they have not called forth such descriptions as those of the arid portions of the coast line, while Diller speaks of the raised beaches of the Oregon coast as being less distinct above eight hundred feet.[3]

It would seem from the above that on the Pacific Coast is an ideal region for comparing the rates and kinds of erosion upon the same initial earth forms, offering an attractive problem for physiographic study.

In conclusion, from the preceding résumé it would appear that an arid climate is an important contributory factor in the development of plains of marine denudation, a factor which so far as the writer is aware has not previously entered into the discussion of the problem of the relative development of plains of subaerial and marine erosion.

Finally, from the discussions under this and preceding topics, the following estimates may be made of the relative rates of erosion under different climates upon average rock materials in a state of topographic maturity. From such a brief study such a statement is clearly nothing but an estimate. Proceeding from what is thought to be the less rapid to the more rapid they would be—

[1] *The Post-Pliocene Diastrophism of the Coast of Southern California*, Bulletin of the Department of Geology, University of California, Vol. I, No. 4, 1893, p. 129.

[2] *The Geomorphogeny of Northern California.* Bulletin of the Department of Geology, University of California, Vol. I, No. 8, 1894, p. 270.

[3] *Coos Bay Folio*, U. S. Geological Survey, p. 1, 1901.

FOR ARID CLIMATES

1. Warm-temperate arid: moderate sun and wind action.
2. Tropical arid: strong sun and wind action.
3. Cold-temperate arid: strong frost and wind action.

FOR RAINY CLIMATES

1. Temperate rainy: moderate mechanical and chemical disintegration.
2. Tropical rainy: moderate mechanical, intense chemical disintegration.
3. Subpolar rainy: intense mechanical, moderate chemical disintegration.

The evidence in regard to the relative position of the varieties of rainy climate does not seem to be as secure as that in regard to the arid climates.

In comparing the rainy climates to the arid it is thought that, on the whole, the rainy climates are the greater destroying agents, but so many factors enter in the final result that it is thought that *a change toward semiaridity will hasten instead of retard erosion* through a weakening of the vegetal covering and a concentration of rainfall. The local accumulations of waste resulting from a movement toward aridity, while apparently indicative of great erosion, should really from their mere presence not be allowed to influence the judgment.

Recent geological times have been marked by climatic oscillations of great magnitude resulting in synchronous erosional and sedimentary oscillations. In past geological times other climatic oscillations must be presumed to have taken place frequently, though normally of much less intensity than during the past ice age. The sedimentary effect of climatic variations as well as stable climates is therefore of geological importance. From the previous discussion it would appear that any variation *from* a temperate climate, either arid or pluvial, would involve a temporary, abnormally rapid increase of rock waste until the regolith had become adjusted to the new conditions. Any variation *toward* these temperate means, such as the normal changes in the temperate zones since glacial times, will result, on the other hand, in a rapid slackening of rock destruction. Through geological time, therefore, the slowly but perpetually fluxing climates would

find a delicate response in the rates of erosion and the kinds of material supplied to the streams. With each climatic oscillation the delicate balance of erosion to stream transportation is thrown out of equilibrium and a wave of disturbance *originating at the headwaters* is sent to, and even beyond, the river's mouth. Even when the nature of the climatic changes at the distant source cannot be determined, they should still be recognized as possible factors in those lithologic distinctions which characterize the successive stages of a sedimentary formation.

The influence of climatic changes upon sedimentation has been tacitly recognized by certain leading writers, either as a hypothesis to account for a regular alternation of marine strata, as has been done by Gilbert;[1] or, through the use of gravel terraces as a means of correlation between glaciated and unglaciated regions. In the latter case they have been distinctly recognized and classified by Davis and Huntington as terraces of climatic origin, and criteria for their distinction have been devised. The relations of climate to erosion appear to be so sensitive, however, and so important, as a causal factor in the variations of stratified rocks, that it would seem desirable to distinguish it clearly as a separate cause, and call special attention to it, as is here done, as of co-ordinate importance with minor movements of the earth's crust. The lack of conscious recognition of this factor has without doubt caused many minor sedimentary changes, and even some greater ones, to be taken as evidence of earth movement, when climatic changes have at least entered as important contributory factors.

Before these waves of climatic effect find record in the strata, however, they are modified by the accompanying variations in the power of transportation and the changes which the sediments undergo before burial on the surface of the flood-plain or bottom of the shallow sea, modifications which will be discussed in the two succeeding parts.

[1] "Sedimentary Measurement of Cretaceous Time," *Journal of Geology*, Vol. III, 1895, pp. 121–27.

[*To be continued*]